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Review

# Sustainable and Renewable Bio-Based Natural Fibres and Its Application for 3D Printed Concrete: A Review

Salmabanu Luhar <sup>1</sup>, Thadshajini Suntharalingam <sup>2</sup>, Satheeskumar Navaratnam <sup>3</sup>,  
Ismail Luhar <sup>4</sup>, Julian Thamboo <sup>5</sup>, Keerthan Poologanathan <sup>2,\*</sup> and Perampalam Gatheeshgar <sup>2</sup>

<sup>1</sup> Institute of Mineral Resources Engineering, National Taipei University of Technology, Taipei 10608, Taiwan; ersalmabanu.mnit@gmail.com

<sup>2</sup> Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, UK; thadshajini.suntharalingam@northumbria.ac.uk (T.S.); g.perampalam@northumbria.ac.uk (P.G.)

<sup>3</sup> School of Engineering, RMIT University, Melbourne, VIC 3000, Australia; sathees.nava@rmit.edu.au

<sup>4</sup> Shri Jagdishprasad Jhabarmal Tibrewala University, Rajasthan 333001, India; Ismail.luhar@gmail.com

<sup>5</sup> Department of Civil Engineering, South Eastern University of Sri Lanka, Oluvil 32360, Sri Lanka; jathamboo@seu.ac.lk

\* Correspondence: keerthan.poologanathan@northumbria.ac.uk; Tel.: +44-19-1227-3077

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**Abstract:** The concept of sustainability and the utilization of renewable bio-based sources have gained prominent attention in the construction industry. Material selection in construction plays a significant role in design and manufacturing process of sustainable building construction. Several studies are being carried out worldwide to investigate the potential use of natural fibres as reinforcement in concrete with its noticeable environmental benefits and mechanical properties. 3D printed concrete (3DPC) is another emerging technology, which has been under-developed for the past decade. The integration of reinforcement is one of the major challenges in the application of this new technology in real-life scenario. Presently, artificial fibres have been used as a reinforcement material for this special printable concrete mixture. However, natural fibre composites have received significant attention by many 3DPC constructions due to their lightweight energy conservation and environmentally friendly nature. These benchmarking characteristics unlock the wider area of natural fibres into the composite sector and challenge the substitution of artificial fibres. Hence, this paper presents a comprehensive review on the current practice and advantages of natural fibres in conventional concrete construction. Subsequently, with a view to the future efficient 3DPC construction, the potentials of natural fibres such as eco-friendly, higher impact, thermal, structural, and fire performance over the artificial fibres were highlighted, and their applicability in 3DPC as composites was recommended.

**Keywords:** natural fibres; sustainability; renewable materials; mechanical properties; 3D printed concrete

## 1. Introduction

There is an emerging demand for bio-fibres as fillers and/or for reinforcement in plastics-composites, due to their flexibility in the course of processing, high specific properties, high specific stiffness, and lower cost on a volumetric basis [1]. In addition, bio-based natural fibre composites are used to enhance the electrical resistance, mechanical, acoustic insulating, and thermal properties together with superior resistance to fracture and good quality [2,3]. Moreover, the natural fibre-composites could be used as panels, sandwich plates, tubes, replacement of wooden fittings, and fixtures, and noise-insulating panels in Civil Engineering applications, where higher mechanical resistance are

not required, but lower maintenance and purchasing cost is needed [4–6]. Fibres are also employed as reinforcement material with composites that can be transformed into dissimilar forms like mats, rovings, fabrics, and yarns [7]. Further, recent studies have revealed that the definite mechanical characteristics of natural fibre-composites are similar to reinforced glass fibre-composites [4,6].

The newer materials based on bio-resins and plant fibres are capable enough to produce greener composite materials, which can alleviate the environmental concerns [8]. The entire consumption of bio-degradable materials is expected to rise at a mean annual rate of closely 13% [9]. Shah [10] forecasted that, by 2020, fibres extracted from bio-based sources will stand for up to 28% of the total market of reinforcement materials [10]. However, the fruitful utilization of the referred fibres relies upon their well-defined mechanical and structural characteristics. The aforementioned attributes of bio-fibres are affected by the vicinity of their origin, conditions of climate, age of plants, and the techniques for extraction. Natural fibres such as hemp, flax, jute, sisal, and coir are a new-fangled class of materials, which have excellent potential in bituminous mixtures [11]. Hence, in order to enhance the tensile strength of these, natural fibres have to fit perfectly to the source material. Oil palm fruit bunch fibre (OPF), jute hemp, betel nut, and coir have examined as reinforcement in polymer composites, due to their desirable attributes as reinforcement [12–15].

Besides, 3D printing has been rapidly growing in recent years [16]. Unsurprisingly, the building construction industry has adopted this technique with the aim of turning the complex building design into reality and developing environmentally friendly structures in large scale. Pegna [17] is the first to implement additive manufacturing technology using cementitious materials. In this study, an intermediate process also was used to attach sand layers together with a Portland cement paste [18]. Afterwards, the large-scale concrete printing practice has been under development in the last 10 years and more than 30 international groups are currently engaged in research [19].

The construction industry is expected to significantly benefit from the adoption of this technology because it is believed that the technology has the potential of reducing the main issues of the construction industry like the construction time, cost, and putting construction workers at risk [20]. 3D printing technology allows buildings to be constructed without the need for the framework, which is a major benefit as formwork makes up approximately 60% of the materials, which assist in the traditional practices of concrete construction. Moreover, 3D printing has been proven to save up to 60% of construction waste, 70% of production time, and 80% of labour costs [21]. This means that utilizing this technology in the construction industry is a more sustainable way to construct building than the conventional concrete structure, and it gives architects more freedom in design. 3D concrete printing of building structures has shown success in commercial aspect. For an example, WinSun, a Chinese architectural company, were the first to develop 3D printing in construction and have since printed offices in Dubai in only 19 days by printing parts and assembling them on site as shown in Figure 1. WinSun demonstrated the potential for higher productivity in construction by directly printing 10 houses in only 24 h, showing that the technology could be deployed in many similar projects [22].



**Figure 1.** The world's first 3D-printed office building is in Dubai (WINSUN, [22]).

However, the material selection and mix design are the critical limiting factor in 3D printing in concrete. In 3D printing concrete specific mixture, which is denser than the typical concrete, without coarse aggregates, steel reinforcement has to be used. Additionally, the mix design of concrete ought to meet the performance requirements of both structural and fire resistance of concrete [23]. Many mix designs have been proposed by past researches [24–29]. However, it was recognized that the mixture with retarders and accelerators, which was used to modify the setting time, showed very high shrinkage and the problem was solved with the inclusion of micro polypropylene (PP) fibres [30]. Figure 2 shows an example of an early showcase of 3D printed concrete (3DPC) structural element with shrinkage cracking. Therefore, researchers incorporated artificial fibres into the printable concrete mixture to increase the tensile properties while overcoming drying shrinkage and cracking problems. However, limited studies have been conducted on the effect of fibre incorporation in 3DPC to date. Hence, the use of such renewable material in 3DPC will potentially help for a sustainable development of 3D printing technology in the building and construction industry.



**Figure 2.** Excessive shrinkage cracking in an early showcase 3D printing mortar element [23].

In summary, it can be said the natural fibres can be adopted in 3DPC to enhance the performance in order to overcome the consistency and shrinkage issues; however, the applicability of natural fibres to the 3DPC is not properly explored. Therefore, in this paper, a comprehensive review of the acquaintance of natural fibres, assets, and current applications that investigates their potential use in 3DPC has been made; the benefits and limitations of the natural fibres in 3DPC and also the need of further research studies are highlighted in the paper.

## 2. Review of Natural Plant Fibres

Natural fibres enclose mainly cellulose emanating from scores of sources; however, common natural fibres are sprung from the plant kingdom. The natural fibres are classified into three major categories, which are natural plant or vegetable fibres, animal fibres, and mineral fibres. Table 1 shows this classification of natural fibres. Figure 3 shows the different types of natural plant fibres [31]. The following sub-section describes the nature and structural components of natural plant fibres. The natural plant fibres have the higher potential to be used as reinforcement in cement and concrete matrices, and the composites made with them were discussed in the following Section 2.2. The previous research studies on these biodegradable natural plant fibre composites and their enhancement on mechanical properties are considered as the positive characteristics on their application in 3DPC material.



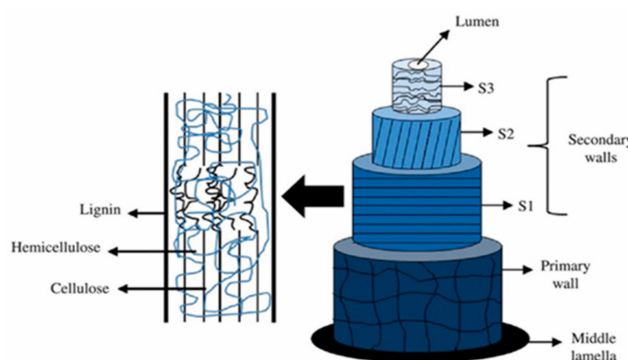
**Table 1.** Classification of Natural fibres [32].

Natural Fibres	Natural Plant or Vegetable (Cellulose or Lignocellulose)	Seed	Cotton, Kapok, Milkweed
		Bast or Stem	Flax, Hemp, Jute, Ramie, Kenaf
		Leaf or Hard	Pineapple (PALF), Banana (Abaca/Manila-hemp), Henequen, Sisal
		Stalk	Wheat, Maize, Barley, Rye, Oat, Rice (Husk)
		Cane, Grass & Reed Fibres	Bamboo, Bagasse, Esparto, Sabei, Phragmites, Communis
		Fruit	Coir or Coconut Fibres
	Animal (Protein)	Wool/Hair	Lamb's Wool, Goat Hair, Angora Wool, Cashmere, Yak, Horse Hair
		Silk	Tussah Silk, Mulberry Silk
	Mineral Fibres	Asbestos Fibrous brucite Wollastonite	

**Figure 3.** Natural plant Fibres (a) Banana; (b) sugarcane bagasse; (c) curauá; (d) flax; (e) hemp; (f) jute; (g) sisal; (h) kenaf; (i) Jute fabric; (j) ramie (k) jute [31].

### 2.1. Structural Composition of Natural Plant Fibres

Cellulose is considered as the key frame-work component of the fibre-structure. In the context of a specific kind of fibre, the “cellulose micro fibrils” contain their cell-geometry that is a feature answerable for the fibre attributes [33]. The cell wall of all the fibres consists of primary as well as secondary layers of “cellulose micro fibrils”. Structure of the fibres builds up in the primary cell wall and gets deposited all through its development. On the other hand, the secondary wall consists of three layers with each one having a stretched chain of helical “cellulose micro fibrils” [34]. Figure 4 demonstrates a schematic structure of a natural plant fibre [35]. The structural composition of plant-based natural fibres are lignocellulosic containing cellulose, hemicelluloses, lignin, and pectin along with waxes. Additionally, smaller quantities of organic, i.e., extractives, and inorganic as ash constituents are present in the structure of plant-based natural fibre [35]. The resistance to decay, colour, and odour of the fibre are assigned to the organic extractives whereas the inorganic components improve its abrasive nature.



**Figure 4.** Structure of Natural Plant fibres [36].

## 2.2. Literature on Natural Plant Fibre Composites

### 2.2.1. Bast Fibre Composites

The investigations on bast fibre composites such as jute, hemp, ramie, and kenaf are summarized in this section. The studies on jute fibre with plastic integrated composites were carried out under the topics of thermal stability, modification, transesterification, crystallinity, durability, weathering, environ-design of components from automotive, and alkylation, and fibre orientation on wear and frictional attitude [37–40]. PP-composites reinforced with jute fibre were estimated for the impact of matrix modify, the influence of interfacial adhesion on creep and energetic mechanical performances, gamma radiation effect, the natural rubber influence, and the silane coupling agent effect [41,42]. Similarly, the polyester resin was employed as a matrix for composites reinforced with jute fibres [43–46]. The results show there is significant improvements in the absorption of water, fracture norms and jagged strength, the elastic characteristics, impact damage portrayal, and the thermal performance of composites. Further, Ray et al. [47,48] have studied the length on the jute fibre resin-treated by alkali and reinforced with vinyl ester. The study reported that the lengthy treatment using alkali has taken away the hemicelluloses and enhanced the crystalline nature, making superior fibre dispersal possible.

The examinations of hemp fibres with PP-composites functionalized via melt grafting reactions with the Glycidyl methacrylate was conducted by Pracella et al. [49]. The fibres alteration and PP-matrix, besides the supplement of a variety of compatibilizers as coupling agents, alter their interfacial attributes and stabilize the melt mix. In comparison with the original system, tailored composites have boosted fibre dispersal in the PP-matrix and advanced interfacial adhesion in consequence of chemical bonding among the fibre and the polymer (i.e., PP plus hemp). The phase behaviour, as well as the thermal stability of the composites were influenced by alteration of the matrix and fibre [49]. Similarly, Li et al. [50,51] investigated and found that the interfacial bonding of hemp fibre with PP has been boosted through chelator and white-rot fungi treatment. Moreover, PP composites reinforced with hemp fibres have displayed greater recyclability [52]. The findings lead to a report that the mechanical attributes of hemp fibre plus PP composites stayed well potted, even though numerous reprocessing cycles. In addition, Epoxy resins were also utilized as a matrix for hemp fibre incorporated composites in the following investigations on the influence of the structural design of fibre on the plunging weight impact characteristics, impact load performance of resin transfer molded composites, performances and attributes of composites for curved pipes, micro-mechanics of the composites, the utility of non-retted hemp as a source of fibre for bio-composites, as well as the impact of hybrid mixes consisted of and nano-clay and soybean oil [53–55]. Furthermore, Kunanopparat et al. [56,57] have investigated the viability of wheat gluten as a matrix for composites reinforced with hemp fibre concerning their impact of plasticization and thermal treatment on the mechanical attributes.

PP composites reinforced with Ramie fibres were manufactured employing a hybrid technique of melt mixing and injection molding courses [58]. He et al. [58] studied various PP composites were produced with ranging lengths of fibre, their quantity, and methods of pre-treatment of fibres.

The findings displayed enhancement in the length of a fibre and their quantity with noticeably augment in strengths like compressive, tensile, and flexural in turn. Similarly, thermo-plastic bio-degradable composites were manufactured with ramie fibres and poly-lactic acid (PLA) plus polycaprolactone (PCL) matrix through the in-situ technique for polymerization [59]. Results highlights that the length and quantity of fibres influences the tensile and impact strengths of this composite.

The compression molded PP composites incorporated with Kenaf fibres have exhibited better flexural and tensile strengths in comparison with other compression molded composites blended with other natural fibres and thermoplastics reinforced with coir [60]. Furthermore, in the past, studies on the mechanical characteristics, energy, impact, thermo-mechanical characteristics, electron beam radiation, and hardening impact of PP composites with natural bast fibres [61–64] highlight that the bast fibres improve the structural and thermal performance of concrete composite. The above study findings showed that the PP and natural fibre composites have made a great impact on strength enhancement on concrete mixtures. Since the PP fibres are widely used in 3DPC material, these PP fibre composites could be used to strengthen and improve the structural and energy performance 3DPC.

### 2.2.2. Leaf Fibre Composites

Banana, sisal, and pineapple leaf are commonly used to produce the leaf fibre composites. Banana fibres had been studied using dissimilar matrices such as cement, aliphatic polyester resin, polyurethane, urea-formaldehyde, PP, polyethylene [PE], polyvinyl alcohol, and polyester to estimate the diverse attributes of resulting composites [65–67]. The mechanical characteristics of PP composites blended with banana fibre having dissimilar fibre lengths and varied compounding courses such as mixer compression molding, direct compression molding, and mixer-injection molding were experimented on by Bledzki et al. [68,69].

Several studies were conducted on polyester composites amalgamated with sisal fibres [70–72]. The epoxy resin was employed in form of a matrix for composites incorporating sisal fibres and has been explored for the study of the reinforcement level and the effect of fibre-orientation on the mechanical and electrical characteristics [72]. Their studies found that amalgamated sisal fibres improve the tensile, flexural, and impact strength as well as hardness of composites elements. Further, Suppakarn et al. [73] identified, Magnesium hydroxide ( $\text{Mg}(\text{OH})_2$ ), and Zinc borate having the molecular formula as ( $\text{B}_2\text{O}_6\text{Zn}_3$ ) with sisal into PP composites improve the fire performance and can be used as flame retardants. This similar method can be employed to the 3D printing technology to improve the fire performance of 3DPC.

The pineapple fibres are another potential leaf fibre to reinforce the polymer composites and it is incorporated with polycarbonate to manufacture useful composites [74,75]. These pineapple leaf fibres treated with silane and integrated with composite displayed the greatest impact strength and tensile strength. This discussion has directed towards a strong insight of using these leaf fibres as a sustainable alternative to the artificial fibres to improve the impact, flexural, and tensile strength of 3DPC, as well as improve the hardness and fire resistance.

### 2.2.3. Bagasse Fibre Composites

The impact of botanical constituents of bagasse on the setting of bagasse incorporated cement-composites, creep attributes of bagasse fibres containing Polyvinyl Chloride (PVC) and HDPE-composites, bagasse fibre treated with silane and blended with cementitious-composites and eco-design and life cycle assessment (LCA) as a strategy for automotive constituents from bagasse blended PP composites were also tested in the past [76–78]. Moreover, the courses of actions like injection and compression molding were conducted with a view to make an assessment for the superior mixing technique for fibres like sugarcane benzylated-bagasse, and bagasse of cellulose as well as PP matrices [79]. Hence, these bagasse fibre composites could be considered as an exemplary replacement for the artificial fibres currently being used in 3DPC mixtures.

The chemical structure and structural composition of natural plant fibres are depicted in Table 2.





### 3. General Characteristics of Natural Fibres

The general characteristic and mechanical properties of natural fibres obtained from previous studies are summarized in Table 2. Though natural fibres demonstrate inferior strength in comparison with synthetic fibres, the specific modulus and elongation at break indicates the potentiality of them to substitute synthetic ones in engineering polymer-composites. The comprehensive review of mechanical, energy, and thermal performance of natural plant fibre composites are presented in the following sub-sections. The applicability of natural fibre composites in 3DPC material in order to improve these characteristics could be claimed from these detailed assessments.

#### 3.1. Mechanical Properties of Natural Fibres

The literature appraisal uncovers that the natural fibres strengthened composites are generally accounted to demonstrate mechanical characteristics as good synthetic fibres. For an instance, Van de Velde and Kiekens [91] have instituted that the mechanical characteristics of flax, sisal, jute, and hemp fibres are admirable making them competent for racing with fibres of glass as regards modulus and strength. A large number of the investigations on Polymer Fibre-reinforced Composites [PFRCs] engross the examinations of mechanical attributes as a function of fibre quantity, the application of exterior coupling agents, and an impact of a range of treatments of fibres [90]. The volume fraction, the orientation of fibre, treatment kind, and physical attributes of the plant fibres vitally impact the mechanical behavior of composites [92]. The most imperative key in designing of PFRCs is the interfacial adhesion amongst the matrix and fibres which is also one of the primary requirements for bonding between the 3DPC layers [93]. The PFRCs showed enhanced mechanical characteristics viz., flexibility, modulus strength, and stiffness, in comparison with synthetic fibres, which are durable with ease of manufacturing in bulky shapes and complex [94]. With changes in the fibre orientation, the material characteristics can be altered to the outer loads and PFRCs combine a higher strength and rigidity with a lower down weight, and their resistance to corrosion is often high [94]. The enormous weight and strength attributes of plant fibres are very encouraging in comparison with metals, and it can be formulated easily by means of moulding processes [69,94,95]. These aspects are one of the key requirements of 3DPC.

Mishra et al. [96] have concluded, subsequent to carrying out investigations on the mechanical performance of natural fibres plus glass-reinforced hybrid composites, that the integration of both plant and glass fibres has improved the tensile, impact, and flexural strengths of the resultant product. A study by Silva et al. [97] has investigated a concentrating on mechano-physical attributes of banana fibres plus silica micro-particles blended epoxy-composites. The results showed that the supplementation of silica and volume fraction has influenced the porosity, modulus of elasticity, flexural modulus, and tensile strength of the composites.

In another study by Sathishkumar et al. [92], the chopped snake grass fibres incorporated composite was manufactured by employing polyester resin for evaluation of the mechanical characteristics of the resulting composites. The upshots lead to reporting that the tensile and flexural strength, as well as modulus of elasticity of the snake grass fibres, blended composite escalates with the boost in the volume fraction of the fibre. However, there is still no fixed standard for fibre quantity in composites. A number of researchers are of the opinion to employ natural fibres up to 40% as optimum in polymer-composites, which can contribute enhanced mechanical attributes. The findings have demonstrated reasonably good-quality electrical and mechanical characteristics and designated their industrial utilization in constructions, electronics, and electrical industries.

##### 3.1.1. Tensile Properties

With regard to mechanical characteristics, the plant fibres can be described as strong performance giving fibres being portrayed by tensile strength, which is found, by and large, to be greater than 200 MPa [98]. Wambua et al. [99] have accounted for different plant fibres after a research study and

found that PFRCs displayed similar upshots for modulus and tensile strength. The eventual tensile stress and the tensile modulus, impact strength of PP composites reinforced with kenaf fibre were found escalating when the acceleration in the context of fibre weight fraction was done. The chopped snake grass fibres isophthalic polyester composites put on show the improved tensile modulus as well as tensile strength with escalating fibre volume fraction as recorded [100]. The integration of kenaf fibres with the thermoplastic natural rubber matrix has shown a boost concerning to Young's modulus and the tensile strength as well as a supplement of maleic anhydride PP enhances ahead the flexural and tensile strengths [101]. The research study on the tensile characteristics of wood fibre wastes incorporated plastic-composites by Jayaraman and Bhattacharya [102] has revealed that the tensile strength remained invariable with the fibre content. However, Ichazo et al. [103] have made a note that supplementing wood flour treated with silane to PP has contributed a boost in the tensile strength and modulus of PP plus wood flour integrated composites.

The investigations on the longer discontinuous natural kenaf fibres plus jute fibres strengthened PP composites manufactured by Lee et al. [104] through hot pressing and carding course of actions, having fibre weight fractions varying from 10 to 70%. The experimental outcomes have made known that the modulus and tensile strength of both jute and kenaf fibres integrated PP composites boosted with enhanced fibre loading and the optimum was attained prior to falling back at a greater fibre weight fraction. A projected solution for housing substitutes by Juarez et al. [94] has engaged sustainable cement-composite blended with Agave lecheguilla fibres. The outcomes designated that the referred lecheguilla fibres have resisted well on exposing to severe environmental conditions and deviations in the context of humidity as well as have exhibited improved tensile strength. The unidirectional biodegradable composites were manufactured using an emulsion kind of poly-lactic acid (PLA) resin and kenaf fibres. The findings of analyses unearthed that tensile strength of kenaf fibres declined when the temperature of 180 °C was maintained for an hour [105].

Oil palm and sisal fibres are integrated with the natural rubber matrix, and the effect of fibre ratio of these composites were scrutinized [106]. An optimistic impact was monitored for tensile attributes, and the longitudinally oriented composite specimens exhibited more enhanced tensile characteristics than samples of the transversely oriented composite. The tensile attributes, resistance to chemical, and void content of palm plus jute fibre blended composites manufactured using palm fibres as skin and jute fibres as core material by Jawaid et al. [107]. These results have proven that the natural plant fibres have noticeably increased the tensile properties of final composite material. Since 3DPC technology requires new printable concrete to be developed that meet specific tensile performance requirements, the idea of incorporating natural fibres into the printable material would certainly create a high impact on future developments.

### 3.1.2. Flexural Properties

The flexural attributes are one of the key parameters for composite materials. These properties are employed for the most part to review the fittingness of the material for utilization of structural kind through confirming its flexural strength, flexural load, flexural modulus, and deflection at failure. A link among flexural strength and fibre quantity plus fibre length was accounted for through research on flexural characteristics of natural fibre composites.

As an illustration, the investigation [92] signifies that the uppermost flexural strength and modulus of chopped snake grass fibre isophthalic polyester-composites are attainable at 25% volume fraction for 120 and 150 mm lengthy fibres. The analysis of flexural attributes done by Joseph et al. [108] of the phenol formaldehyde composites incorporated with fibres of banana and glass has uncovered that the highest possible fibre length necessitated for fibres of banana and glass is dissimilar for blending a phenol-formaldehyde resole matrix. Aziz and Ansell [109] have monitored the influence of fibre alignment and alkalization of longer and arbitrary kenaf and hemp fibres, which were enclosed in polyester resin and were hot-pressed to develop a composite. The results disclosed that alkalized and longer fibre-composites contributed elevated flexural strength and flexural modulus and a comparison

was made for the composites manufactured from the as-presented fibre. Mysamy and Rajendran [110] have summed up the study that good-quality chemical bonding among continuous alkali-treated agave fibres and an epoxy matrix contributed an enhanced flexural modulus, impact strength, and flexural strength of the composites. The combination of the plant plus glass fibres integrated polymers is increasingly employed in a number of fields and there found to be a noteworthy enhancement in flexural attributes.

Yao and Li [111] have conducted a methodical study on flexural parameters of sandwich-composites incorporated with bamboo fibres. The outcomes displayed that the flexural strength of the composites integrated with bamboo fibres on the base can be enhanced, which developed a tension layer and the mortar sheet on the pinnacle acting as the compressive layer. The composites incorporated with fibres of sisal when tested for mechanical attributes have put on show noticeably improvement on supplementing silica micro particles. Nevertheless, the silica supplement has not influenced the flexural strength when the interaction among the particles of silica and fractions of fibres are taking the most important part of the flexural modulus.

Usually, the composites incorporated with treated short fibres and undergone post-curing contributed enhanced values for flexural modulus in comparison with those enclosing untreated fibres. Evidently, the adhesion among the fibre and matrix enhanced through alkali treatment [112]. The best possible value of the flexural modulus was reported at 20 wt%, which was roughly 4.3 GPa, for composites having been treated as well as subjected to post-curing [113]. Hence, it is obvious that the natural fibres have great influence towards the flexural strength enhancement in these composite concrete materials. Therefore, these natural plant fibres could be integrated with 3DPC material as a novel approach to resolve the anisotropic flexural strength issues recognized with the layered concrete structures.

### 3.1.3. Impact Properties

The impact property of PFRCs relies upon numerous factors such as the nature of the constituent, matrix fracture, fibre and matrix interface, the construction and geometry of the composite, fibre pullout, and the conditions at the time of examinations [47,114,115]. To simulate authentic impact through a foreign object, several courses for testing have been proposed by many researchers, as the impact resistance of materials of the composite is a complex subject [47,114–116]. Notably, Sezgin and Berkalp [116] accounted that elevated values of impact can be attained by supplementing towering impact-resistant fibres to the external layers of the composites. With reference to laminated composite, the impact strength is boosted with the adding up of filler up to a definite limit and after that, it started decreasing if further add-on is made [116]. The upshots indicated that impact characteristics rely upon the concentration of the fillers and decrease in density of the composites, which in turn, highly dependent upon the quantity of fillers and fibres.

Pothan et al. [114] have explored short polyester-composites integrated with banana fibres to comprehend the impact of fibre quantity and length on the impact strength of the referred composites. Sanjay et al. [117] estimated the impact behavior of polyester-composites reinforced with banana plus E-glass fibres, through comparison of laminates with dissimilar composition. Additionally, Mysamy and Rajendran [110] have explored the impact properties of Agave fibre epoxy-composites. Luciano et al. [118] have explored the resistance to the impact of hybrid-composites enclosing silica nanoparticles plus sisal fibres, and results confirmed that the composites manufactured with unidirectional fibres sans any treatment and silica nanoparticles by 2 wt% have put on show an augmented impact resistance and mitigated entire porosity. The study of Abdul Khalil et al. [119] revealed that the elevated strength of fibres of glass has piloted to better impact strength in polyester-composites blended with glass plus oil palm empty fruit bunches. In addition, Wambua et al. [99] have made a comparison of the impact strength of coir, kenaf, and jute integrated composites and wrapped that coir fibres-composites have demonstrated elevated impact strength; however, its other mechanical characteristics were inferior as compared to kenaf and jute

fibres-composites. Yuanjian and Isaac [120] reported that composites enclosing softer and longer wood fibres have shown more enhanced impact resistance than harder and shorter wood fibres incorporating composites.

Ramakrishna and Soundararajan [115] have studied the resistance to impact loading of plant fibres containing cement mortar and exposed to impact loading employing a projectile test whereby four dissimilar fibres contents and three unlike fibre lengths were employed. The findings indicated that the supplement of the plant fibres has boosted the impact resistance by three to 18 times more than that of plain mortar slab. The mechanical attributes of composites blended with synthetic cellulose and Abaca fibres have been explored [121]. The manufacturing of composites was done through employing combined moulding method pursued by two-step extrusion course and injection moulding. Potentially, the plant fibres are more competent for reinforcing the composites than artificial fibres and Abaca fibres appear to contribute an elevated rigidity to the composite [121]. In summary, the outcomes of these investigations have provided fundamental insights on the development of printable concrete mixture with natural plant fibres in order to improve the impact properties.

#### 3.1.4. Hardness Properties

The hardness of composite can be regarded as a measure of resistance of constituting materials to local plastic deformation. Sanjay et al. [122] have measured the hardness of dissimilar laminates manufactured from banana plus E-glass fibres integrated polyester-composites by a range of stacking sequences. The result unveiled that an augmented number of banana fibre layers declined the hardness of the composites. Ramanaiah et al. [123] have developed polymer matrix containing composite integrated with natural Borassus seed shoot fibres and observed that hardness of the composites declined with a boost in the quantity of fibres. Lee et al. [124] conducted elastic modulus and hardness examinations on PP composites blended with cellulose fibres formulated by the Nano indentation technique. Right from the fibre to the matrix, a line of indents was found developed, and there were a hardness gradient and modulus across the inter-phase area. However, to address the fluctuating hardness properties of different layers in the 3D printing technology, the natural plant fibres could be used as an interlayer reinforcing material.

#### 3.1.5. Fatigue Properties

The natural fibre-reinforced composites are exposed to fatigue properties, fatigue failure, and fatigue behavior [125]. Escalating ratios of stress can escort to enhanced fatigue performance in natural fibre integrated-composites. Their fatigue lives not merely the impacts of a load, but also other investigational input variables like stress ratio, highest stress, and orientation of fibres can be taken into account [126]. On the other hand, the output variables are the quantity of cycles to load frequencies and failure stress ratios.

Brunner et al. [125] have built up a regular practice for the portrayal of inter-laminar de-lamination propagation in highly developed composites under fatigue loading situations. Further, Dick et al. [127] also have performed examinations of bending on the composites enclosing glass filled poly-carbonates with interest to appraise the residual strength and fatigue life following the cyclic loading. This study have monitored that the fatigue strength boosts with an augment in cyclic loading.

The fatigue cracks growth behavior and the fracture resistance of pulped fibres of banana, sisal, and bleached eucalyptus pulp integrated blast furnace slag cement was monitored by Savastano et al. [128]. This study found that the fracture hardness of this composite is superior to the plain cement-paste as well as the fibres were met with as well potted even subsequent to the period of exposing for two years to the cement-environment. This illustrates the positive consequence of natural fibres in composite concrete material and leads to the potential use of them in 3DPC material.

### 3.2. Absorption of Water/Moisture Properties

The absorption of water in the form of moisture is one of the most unwelcome aspects in natural plant fibres, since it mitigates the interfacial bonding amongst the matrix and fibres [129]. The hydrophilic behavior of fibres of the plant creates complexity in obtaining a good-quality adhesion among matrix and fibres contributing to greater absorption of water by the plant fibres that deteriorates the composite-product in utilizations [129]. The investigations on the water absorption lead to determine the impact of moisture on the de-bonding, loss of strength, and size of the composites [130]. The absorption of water by the composites integrated with plant fibres is a critical restraint for product utilization as plant fibres absorb a higher quantity of water as compared to artificial fibres [131]. The absorption of water percent in the composites relies upon two factors; one is temperatures prevailing in the atmosphere, and another is quantity of fibres [132].

Jumaidin et al. [133] have confirmed the absorption of moisture of thermoplastic sugar palm starch plus agar amalgamated specimens. Azwa and Yousif [134] have summarized that composites reinforced with alkali-treated kenaf fibres have displayed lesser absorption of moisture than the composites enclosing untreated fibres. Due to the presence of hemicellulose and least voids present in the treated fibres, moisture might not be upheld inside the composites. The results of Sanjay and Yogesha [117] have explored the incorporation of jute plus kenaf together with E-glass integrated woven fabric-composites on the behavior of absorption of water and identified that the blending with E-glass has trimmed down noticeably the capability of the absorption of water by the composites. Hom et al. [135] have analyzed the behavior for water absorption of unsaturated polyester-composites incorporated with non-woven hemp fibres. Their study ultimately reported that the augmented content of cellulose and amplified voids have altogether contributed a boosted moisture uphold and fibre volume fraction of the composites.

Le Duigou et al. [136] have tested the impact of seawater ageing on the attributes of biological composites. Results exhibited that the deteriorating of the interface amongst a matrix of poly L-lactic acid (PLLA), and flax fibre is one of the key features triggering the smashed-up mechanism persuaded by absorption of water. Instead, the attributes of water absorption by PP composites blended with coir plus sisal fibres utilizing water at three unlike temperatures at 23°, 50°, and 70 °C, were tested.

The research study by Zamri et al. [137] explored the mechanical characteristics of composites integrated with fibres of jute plus glass possessing condition for the absorption of water. The referred composites were exposed to water absorption attributes and examinations conducted through immersion of composite sample into three dissimilar water conditions, i.e., distilled water, acidic water, and seawater for three weeks at ambient temperature. The impact of varying conditions for water surroundings on the compression and flexural properties have been tested, which recorded that the jute fibres containing composites are not fitting for underwater utilization. Din et al. [138] on the attribute of absorption of moisture of composites manufactured by incorporating with coconut shells under the impact of the flow of CO<sub>2</sub>. The coconut shell was impregnated with potassium hydroxide (KOH) solution and carbonized as well in advance, which displayed noteworthy enhancement in the property of absorption of water.

The surface moisture plays a vital role in the interlayer bonding strength between printed layers compared with conventional mold cast concrete. Hence, the moisture properties and water absorption of natural plant fibres has to be studied extensively to identify the effect on the mechanical properties of 3DPC structural elements.

### 3.3. Thermal and Energy Properties

The classic functional attribute of polymer-composites reinforced with natural fibres, in particular, transverse thermal insulation characteristics is largely derived from the intrinsic inner morphology of natural fibres [65,139]. Typically, the thermal conductivity of natural fibres is largely inferior to conventional mineral fibres of carbon and glass. Consequently, improved display of thermal insulation is effortlessly obtained through incorporation with natural fibres in the referred composites [139,140].



The thermal attributes of the natural fibre-composites can be managed employing modifications in the values for thermal conductivity of matrix and the inner microstructure of the natural fibres [65,139,140].

Joseph et al. [139] have studied on the crystallization and thermal behaviors of PP composites integrated with short sisal fibres and found that these fibres have put on show the superb attributes subsequent to the chemical treatment by using maleic anhydride-modified PP, a urethane derivative of polypropylene glycol (PPG), as well as potassium permanganate ( $\text{KMnO}_4$ ). Feng et al. [140] have accounted that the application of maleated polypropylenes (MAPP) with kenaf fibre plus PP incorporated composites have altered its melting nature and crystallization too. Analogously, Annie Paul et al. [65] have explored the physico-thermal characteristics of banana fibres plus PP amalgamated composites and the upshots exhibited that the thermal diffusivity and conductivity of these composites slimmed down with fibre loading following the chemical treatment of the fibres with unlike concentrations of sodium hydroxide NaOH.

The thermo-gravimetric analysis findings have signified that the supplement of fibres from kenaf plant into the epoxy has enhanced to some extent both the thermal stability and charring [134]. Setsuko and Nobuo [141] have examined the impact of thermal degradation on the mechanical attributes of wood flour incorporated polymer-composites. The physico-thermal characteristics of PFRCs were taken into account by Idicula et al. [142] for their research study and unearthed that the reinforcement of fibres of the plant with those of glass enhances appreciably the capacity of transfer of heat of the materials. Boopalan et al. [143] have explored the thermal and mechanical characteristics of epoxy-composites integrated with jute plus banana fibres. Additionally, one more research study by Jumaidin et al. [133] on agar and sugar palm starch amalgamated composites displayed that the agar supplement has enhanced Young's modulus and tensile strength and also improved the thermal characteristics of composites blended with thermoplastic sugar palm starch, concerning melting temperature and glass transition temperature. These positive attributes of natural plant fibres in thermal and energy performance have shown their significance impact on composite concrete materials. Thus, the natural plant fibres could be considered as a feasible replacement for artificial fibres to enhance the insulation, thermal and energy behavior of 3DPC material.

### *3.4. Limitation in the Application of Natural Fibres in the Construction Materials*

Previous studies on the composite with natural fibres illustrate that this natural fiber can be used as an alternative to the artificial fiber to improve the structural, thermal, fire, and energy performance. However, higher water absorption, weak bonds, origin of fibre, expansion conditions of plant, and lower degradation temperature limited the application of natural fibres in the construction material. The inherent higher absorption of moisture brings dimensional modifications in the lingo-cellulosic based fibres [40]. The competence of a reinforced fibre composite relies upon the interface of fibre and matrix and the capability to shift the stress from the matrix to the fibre. The referred stress transfer efficiency acts dominantly in confirming the mechanical attributes of the composite. The hydrophilicity of natural fibres results in higher absorption of moisture and weak bond to hydrophobic matrices. However, natural fibres can be treated to enhance their bonding to materials of the matrix [144].

The other challenges include large disparity of mechanical attributes, inferior eventual strength, lower down elongation, issues with nozzle flow in injection moulding machines, bubbles present in the product, and weak resistance to weathering represented by natural fibres [12–15]. Further, the course of decortications might cause effects (knees, bow, and dislocation) on the mechanical properties of composites products, as these shortcomings are not distributed homogeneously over the fibre length and may act as a significant role in the resistance to rupture and mechanical strength [145]. In order to put off the generation of the referred drawbacks, it is vital to comprehend the impact of the entire lingo-cellulosic course of action on the dimensional attributes of the fibres' wished-for application for mechanical reinforcement. Despite these disadvantages, the sustainable nature; reasonable tensile and flexural strength improvements; and significant improvement in the impact, thermal, energy and fire performance of natural fibre compared to artificial fibre lead the potential to use in the 3DPC.

In addition, to address these challenges of using natural plant fibres in the 3D printing technology without hindering its overall advantages, further studies had to be conducted.

#### 4. Fibre Reinforcement Application in 3DPC

This section widely discusses the existing fibre usage in the developed 3DPC materials and addresses the potential utilization of natural fibres for the development of 3DPC composite materials. 3D printing with concrete composite materials is a developing technology and offers an active area of research. However, similar to any new technology, there are challenges in applying this technology in construction industry. Selection of printable concrete mixture is the prime limiting factor in 3D concrete printing and the main challenge in the development of a printable mix is to have balancing stability with required flow and self-compaction concrete, which are conflicting aims [24,26,27]. As the printable concrete mixture does not comprise coarse aggregates and the incorporation of reinforcement bars are not involved in the printing process, fibre reinforcement plays a major role in the tensile capacity of 3DPC structures. Fibre-reinforcements can be incorporated in the 3D printable concrete mixture as structural reinforcement to enhance the mechanical properties such as toughness, ductility, fatigue resistance, impact resistance, and especially the tensile strength and also to control shrinkage and thermal changes. Such printable concretes were developed by various researchers using different types of fibres such as steel, glass, carbon, synthetic, and natural fibres [146,147]. Furthermore, the material with fibres must be extrudable through a nozzle smoothly without creating blockages due to fibre inclusion. Moreover, the deposited layers should not collapse under the load of subsequent layers, and a good bond strength between the layers must be ensured to achieve required hardened strengths.

From the literature review, it is noticeable that the investigations on fibre reinforced extrusion-based 3DPC gained much attention recently, and it is crucial for practical application. Many studies have been conducted using artificial fibres in 3DPC mixture to date. A study by Korniejenco et al. [148] clearly discussed the impact on the properties of geopolymer composites with short and long fibres used for 3D concrete printing. The author classified the fibre reinforcements used for the 3D printed geopolymer composites as short fibres (steel, glass, PP, polyvinyl Alcohol (PVA), polyphenylene benzobisoxazole (PBO), flax and carbon, and long fibres (steel, carbon, aramid, and other micro cables).

Initially, Le et al. [30] developed a high performance printing concrete with the inclusion of micro PP fibres. Feng et al. [140] used fibres in powder based concrete printing and observed significant strength reduction between layers due to formation of air bubbles. Afterwards, Hambach et al. [149] presented a nozzle injection technique for carbon fibre reinforced cementitious material including the material preparation, fibre alignment, rheology, and the fracture behavior. Likewise, Panda et al. [150] studied the effect of short glass fibres in the mechanical performance of 3DPC material, and Paul et al. [151] investigated the fresh and hardened properties of 3D printable cementitious material with glass fibres. Moreover, Shakor et al. [152] analyzed the impact of deposition velocity in the addition of E6-glass fibre on extrusion-based 3D printed mortar.

Lately, Nematollahi et al. [153] investigated the effect of PP fibres on the fresh and hardened properties of 3D-printed fibre-reinforced geopolymer mortars, and Nematollahi et al. [154] also investigated the effect of three kinds of plastic fibres (PVA, PP, and PBO fibres) on inter-layer bond and flexural strengths of extrusion-based 3D printed geopolymer. Additionally, Yu et al. [155] investigated the effect of strain-hardening cementitious composite (SHCC) with PVA fibre on the tensile and compressive performance of 3DPC material. Furthermore, printable engineered cementitious composites (ECCs) with high-density polyethylene (HDPE) fibres was developed by Ogura et al. [156], and Ding et al. [157] also examined the anisotropic behavior of PE fibre reinforced concrete material for 3D printing under bending.

Hambach and Volkmer [158] were the first to endeavor adding short different types of fibres (carbon, glass, and basalt fibres) into 3D printed composite of Portland cement paste. Similarly, Shakor et al. [159] investigated the mechanical strength variation of 3D printed mortar with different types of fibres such as E-glass fibre length, AR-glass fibre length, carbon fibre, and PP fibre. The fibres

were added in different percentage ratios in order to obtain suitable workability and efficiency for the purposes of extrusion and construction.

Bos et al. [160] studied the effect of adding short straight steel fibres on the failure behavior of print mortar, which has been studied through several tests on cast and printed concrete, on different scales. Likewise, Al-Qutaifi et al. [161] investigated the effect of hooked end steel fibres and PP fibres on the mechanical properties of layered geopolymer material for 3D printing. The results showed negative effects on the bond strength between subsequent layers due to fibre inclusion and mentioned that steel fibres, as a reinforced material for 3DPC, are not recommendable. Following that, Chu et al. [162] developed an extrudable high strength fibre reinforced concrete (HSFRC) and studied the influences of nanoparticles and carbon, steel, and glass fibres on their extrudability, buildability, and strength properties. The study also claimed that the inclusion of steel fibres is more effective in strength enhancement but less effective for the interlayer bonding characteristics compared to the addition of carbon or glass fibres. Pham et al. [163] also studied the influence of steel fibre length and volume fraction on the mechanical performance of printed concrete. Moreover, Arunothayan et al. [164] developed a 3D-printable ultra-high-performance fibre reinforced concrete (UHPFRC) with steel fibres.

In addition, few researchers have focused on using natural fibres in 3D printable concrete material. Bos et al. [165] explored the mechanical attributes of flax plus PP composites, produced with a batch kneading and an extrusion progression, and the attributes were confirmed. Similarly, Korniejenko et al. [166] focused on fly ash-based fibre-reinforced geopolymer composites with green tow flax and carbon fibres. Furthermore, Ma et al. [167] conducted an experimental investigation to identify the optimal basalt fibre content in an extrudable concrete mixture based on suitable printability as well as on mechanical performance. Mechanical enhancement was noticed with the fibre alignment along the print direction, and this was achieved by keeping the nozzle diameter smaller than the length of the basalt fibre, which could be achieved by using natural fibres. It is also noteworthy that the Italian company Wasp has used straw and rice husk as an insulation material for the first 3D printed house [168]. In addition, Australian based bio-technology company called Mirreco developed 3D printed hemp panels to build both residential and commercial building projects [169]. Table 3 summarises the general characteristic and mechanical properties of artificial fibres used in 3DPC materials in previous studies.

The applicability of natural fibres in 3DPC is studied, since they possess advantages with their mechanical properties, low density, environmental benefits, renewability, and economic feasibility. According to the detailed review on PFRCs and the mechanical attributes of bio-based natural fibre composites, the incorporation of natural fibres in 3DPC mixture will be a sustainable solution towards the new technology. The positive aspects of using these composites in printable mixtures are superior fibre dispersal, which prevents blockages in printing process; acceptable strength enhancements; wide range of fibre lengths; bendable behavior of natural fibres; improved interfacial bonding of natural fibres with PP fibres; enhanced thermal and energy performance; and better insulation properties. The water and moisture absorption are the most adverse aspects of natural fibres, since they cause poor interfacial interaction between the polymer matrix and the fibre. However, these fibres could be optimized by chemical treatments and surface treatments to overcome this issue. Although, the structural elements printed using these natural fibres are most likely to perform as non-load bearing elements, this could be implemented in wide range of applications.

**Table 3.** Properties of artificial fibres from past germane studies.

Reference	Fibre Type	Length (mm)	Diameter ( $\mu\text{m}$ )	Tensile Strength (MPa)	Young's Modulus (GPa)	Density ( $\text{g}/\text{cm}^3$ )	Specific Gravity ( $\text{g}/\text{cm}^3$ )	Elongation (%)	Melting Temperature ( $^{\circ}\text{C}$ )	Thermal Expansion Coefficient $10^{-6} \text{ K}^{-1}$
Le et al. [30]	PP micro	12	180							
Hambach et al. [149]	Carbon	3	7	4000	238			1.7		
Panda et al. [150]	Chopped glass	3/6/8				1.7–2.2				
Paul et al. [151]	Glass	13.5		1500	74	2.7		2		
Shakor et al. [152]	E6-glass (Trojan)	6 $\pm$ 1	100	2500–2700	81		2.62–2.63			6
Nematollahi et al. [153]	Polyvinyl Alcohol (PVA)	6	26	1600	37	1.3		6.0		
	PP	6	11.2	880	13.2	0.9		17.6		
	PBO	6	12	5800	270	1.56		2.5		
Yu et al. [155]	PVA	12	39	1275	16.9	1.30				
Ogura et al. [156]	HDPE microfibrs	6	12	3000		0.97				
Ding et al. [157]	PE	6/12	20	2400	100	0.97			150	
Hambach et al. [170]	Carbon (HT C261)	3	7	3950	230					
	Glass (AR Force D-6)	6	20	3500	72					
	Basalt (BS 13 0064 12)	6	13	4200	93					
Shakor et al. [159]	PP	6	100	1300	7.2		0.91			
	Carbon	12	44	4000	240		1.67			
	E-Glass (Trojan)	6	100	1400	72		2.60			
	AR-glass	6	100	1700	72		2.70			
	Hooked-end steel	40	615	1160						
Al-Qutaifi et al. [161]	PP	50	22			0.91				
Chu et al. [162]	Carbon	6	7	>3000	250		1.80			
	Steel	13	200	>2000	210		7.85			
	Glass	12	7	>1700	75		2.68			
Pham et al. [163]	Steel	3/6	200	2000		7850				
Arunothayan et al. [164]	Steel	13	200	2500	200	7.85				
Korniejenko et al. [166]	Carbon	5	8	2800–5000	230	1.6/2.0		1–1.5		
Ma et al. [167]	Basalt	18	12–15	2180	87.2	2.55		2.55		

## 5. Discussion and Conclusions

The key goals in the construction industry are to reduce the cost, mitigate the carbon dioxide emissions level, and conservation of natural material resources by employing other durable materials in their place. This 3D printing technology has the capability to fulfill these key goals, as it has several benefits such as improved geometrical freedom and greater safety in construction. However, this 3D printing method needs to be improved in terms of contradictory rheological requirements, weak interlayer bonding, structural performance, and material properties before it is employed in the construction. Further, 3DPC needs reinforcement to resist anticipated shear, tensile, flexural, and axial loads and achieve adequate ductility, which is the ability to undergo large deformation while sustaining the load from natural and manmade hazards.

Currently, artificial fibres are used as a reinforcement in the 3DPC, and their nature is not eco-friendly, and they require significant energy to produce. Thus, the application of natural fibres acts as reinforcement to produce 3DPC towards sustainable green construction. Globally, there exist thousands of differing fibres and in fact, merely a few of these have been investigated so far. The review suggested that the flax, hemp, jute, sisal, kenaf, and ramie fibres were explored at length and utilized for a variety of different applications. Nevertheless, presently, the fibres of banana, pineapple leaf, and bagasse are turning out to be eye-catching with full interest and significance in both research studies as well as for potential applications on account of their precise unique attributes and, of course, the accessibility. Further, the research studies highlighted that there is a significant improvements in the tensile and flexural strength of natural fibres composites. Moreover, the impact and thermal energy performance of natural fibre is higher than the artificial fibre. These advantages and eco-friendly nature of natural fibre can be a sustainable alternative to the artificial fibres to improve the structural, thermal, and energy performance of 3DPC.

## 6. Future Recommendations

Since 3DPC is a novel construction technique and it is still under development, this review is presented as an initiative approach for future investigations on application of natural fiber in 3DPC. Thus, the following insights have been recommended for future research studies.

- Even though the use of natural fibers is increasing certain mechanical properties of composite concrete, the adverse effect on workability is yet to be assessed.
- More investigations are needed to develop printable concrete mixtures with natural fibres and to explore the structural and thermal behavior.
- In contrast with conventional concrete manufacturing, the life cycle assessments of 3DPC with natural fibres, reduction of carbon dioxide emissions and embodied energy are required to be studied in further research.

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